Global and regional seasonal variability of mid-tropospheric CO_2 as measured by the Atmospheric Infrared Sounder (AIRS)

Thomas S. Pagano, Edward T. Olsen, Hai Nguyen
California Institute of Technology, Jet Propulsion Laboratory
4800 Oak Grove Drive, Pasadena, CA, USA 91109

ABSTRACT

The Atmospheric Infrared Sounder (AIRS) is a hyperspectral infrared instrument on the Earth Observing System (EOS) Aqua Spacecraft, launched on May 4, 2002 into a near polar sun-synchronous orbit. AIRS has 2378 infrared channels ranging from 3.7 µm to 15.4 µm and a 13.5 km footprint at nadir. AIRS, in conjunction with the Advanced Microwave Sounding Unit (AMSU), produces temperature profiles with 1K/km accuracy on a global scale, as well as water vapor profiles and trace gas amounts for CO_2, CO, SO_2, O_3 and CH_4. AIRS CO_2 climatologies have been shown to be useful for identifying anomalies associated with geophysical events such as El Niño-Southern Oscillation or Madden–Julian oscillation. In this study, monthly representations of mid-tropospheric CO_2 are constructed from 10 years of AIRS Version 5 monthly Level 3 data. We compare the AIRS mid-tropospheric CO_2 representations to ground-based measurements from the Scripps and National Oceanic and Atmospheric Administration Climate Modeling and Diagnostics Laboratory (NOAA CMDL) ground networks to better understand the phase lag of the CO_2 seasonal cycle between the surface and middle troposphere. Results show only a small phase lag in the tropics that grows to approximately two months in the northern latitudes.

Keywords: NASA, Satellite, Hyperspectral, Atmosphere, Carbon Dioxide

1. INTRODUCTION

The Atmospheric Infrared Sounder (AIRS) on the Aqua spacecraft measures the hyperspectral infrared spectrum of the atmosphere from 3.7 µm to 15.4 µm with nearly twice global daily coverage (Chahine, 2006). The Advanced Microwave Sounding Unit (AMSU) is a microwave radiometer with 15 channels ranging from 23.8 GHz to 89 GHz. National Weather Prediction (NWP) centers worldwide assimilate the AIRS and AMSU radiance data. Assimilation of AIRS data has resulted in the highest forecast improvement of any other single sensor. AIRS, in conjunction with AMSU, produces temperature profiles with an RMS accuracy of 1K/km on a global scale, as well as water vapor profiles and trace gas amounts for CO_2, CO, SO_2, O_3 and CH_4. AIRS data are used for studies of atmospheric transport and global circulation, atmospheric chemistry, climate processes and anthropogenic impacts to Earth's atmosphere. A description of the AIRS data products and a comprehensive survey of science accomplishments covering the period from launch to 2010 are given in prior publications[1,2].

2. AIRS CO2 MONTHLY REPRESENTATIONS

The CO_2 data used in this analysis are produced by the National Aeronautics and Space Administration (NASA) AIRS Project and are unique in the sense of high global spatial coverage, i.e., not being limited to only sunlit or clear regions. The data are produced using the method of Vanishing Partial Derivatives (VPD)[3]. The VPD method solves for the CO_2 concentration by iteratively minimizing the difference between the AIRS cloud-cleared observed radiances and radiances calculated for the AIRS retrieved atmospheric state using the AIRS Radiative Transfer Algorithm (RTA). The VPD method is based on coordinate descent methodology, that is, it applies the minimization independently and sequentially to four geophysical parameters that impact the radiance of selected channels used to retrieve CO_2: atmospheric temperature, water vapor, ozone, and carbon dioxide. The process is iterated until the radiance residuals for all parameters are minimized or the change in CO_2 falls below 0.25 ppm. Extensive quality controls applied during the retrieval include quality of the AIRS geophysical products, monotonically decreasing radiance residuals from one iteration to the next, and spatial homogeneity of a 2×2 set of retrievals (clusters) required to be within 2 ppm in the

RMS sense. The resulting "Level 2" standard product achieves a yield of over 15,000 mid-tropospheric CO_2 retrievals per 24-hour period, each with a horizontal footprint of 90 × 90 km centered over the area where acquired.

AIRS Level 2 CO_2 retrievals were compared to aircraft measurements made in the middle troposphere by Matsueda, taken over the Pacific Ocean at ≥10 km altitude between Australia and Japan from Sept. 2002 to March 2004[4]. Comparisons of the individual AIRS CO_2 daily concentrations to the concentrations measured by Matsueda give a RMS deviation of less than 3.0 ppm with a bias of approximately 1.0 ppm. The distribution of differences is Gaussian allowing accuracy improvement due to averaging in the monthly data products. For 7 clusters used in a month, the RMS error is 1.2 ppm with a bias of 0.4 ppm.

Monthly representations of the AIRS global mid-tropospheric CO_2 data are generated from the AIRS Level 3 (L3) Monthly Gridded CO_2 data files. These L3 files are generated by averaging the valid Level 2 standard data product in a 2º x 2.5° grid for each month. First the L3 data are detrended, i.e., the annual growth in CO_2 is removed on a per-grid basis. Then data for a given month are averaged over all years for all grid cells. The resulting product consists of 12 representations, one for each month, with mean, standard deviation, and number of counts in each grid cell. An example representation of mid-tropospheric CO_2 for the month of July is shown in Figure 1. Zonal averages of the representations as a function of month in the year are shown in Figure 2. Note, we see a distinct seasonal cycle with a peak sometime in May for the Northern Hemisphere. A complete description of the method of retrieval for the AIRS representations and the statistical significance of the product is given in a prior writing[5].

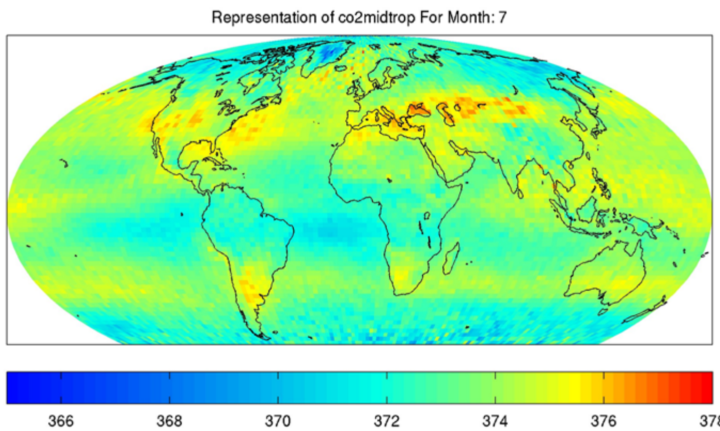

Figure 1. Global Representation of Mid-Tropospheric CO2 from the AIRS instrument for the month of July.

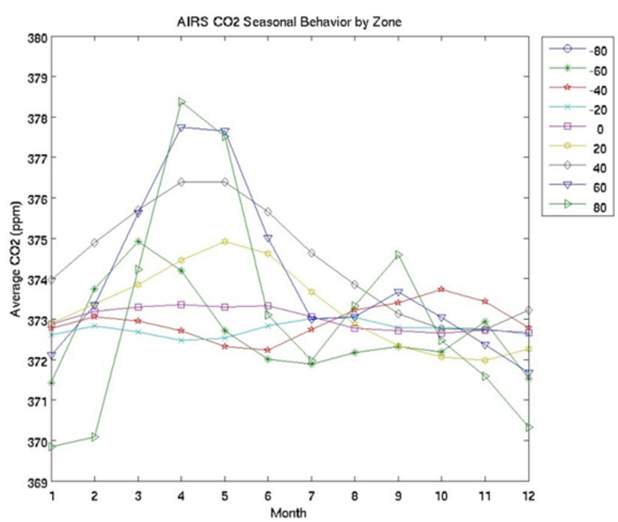

Figure 2. Zonal Average of AIRS Mid-Tropospheric Carbon Dioxide Representations.

3. GROUND-BASED CO2 MEASUREMENTS

Comparisons with ground-based networks of CO_2 measurements will allow us to identify the phase lag between the seasonal cycle measured in the middle troposphere and the surface. We start with measurements of the Scripps ground-based network consisting of 13 locations from Alert, Canada to the South Pole[6]. We use the monthly CO_2 concentrations in micro-mol CO_2 per mole (ppm) reported on the 2008A SIO manometric mole fraction scale without smoothing or interpolation. Figure 3 shows an example of the Scripps data for the La Jolla site overlain with data obtained from the AIRS instrument for the same location and timeframe. We can see from the figure that the amplitude is lower than that from the surface, but identification of a phase lag requires fitting the data to a sinusoidal function with amplitude and phase. This was performed and results presented in the next section.

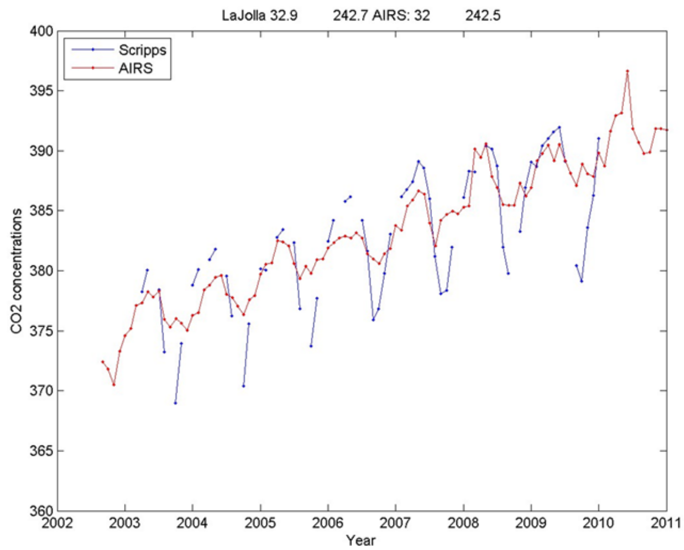

Figure 3. Scripps data for Lajolla, CA over timeframe of AIRS measurements, overlaid with AIRS monthly L3 data for that location.

The second set of surface data used in the analysis are obtained from the National Oceanic and Atmospheric Administration Climate Modeling and Diagnostics Laboratory (NOAA CMDL). The CO_2 mixing ratios reported in these data sets were measured by a nondispersive infrared absorption technique in air samples collected in glass flasks at NOAA ESRL Carbon Cycle Cooperative Global Air Sampling Network sites[7]. Over 84 sites are used in this data set and their locations are shown in Figure 4. Monthly representations of these data are also constructed in the same way as for the AIRS data, by first detrending the data for the annual growth rate and averaging over a given month for all years available in the data set. Zonal averages of the representations for each month are shown in Figure 5. There may only be a few data points in the zonal averages for some zones which will impact the uncertainty in the results.

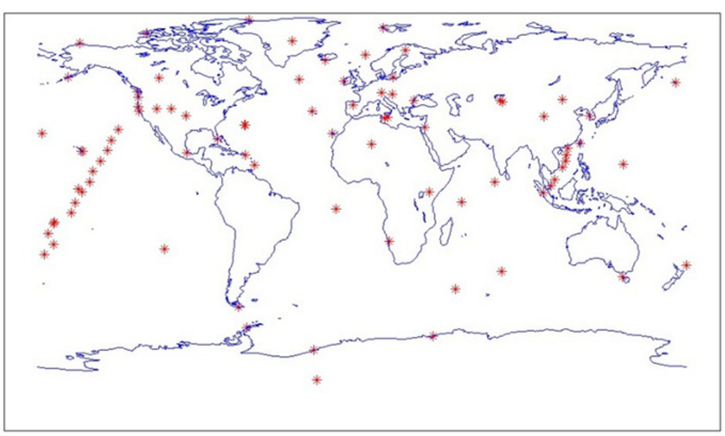

Figure 4. Locations of the CMDL data used in the comparison study.

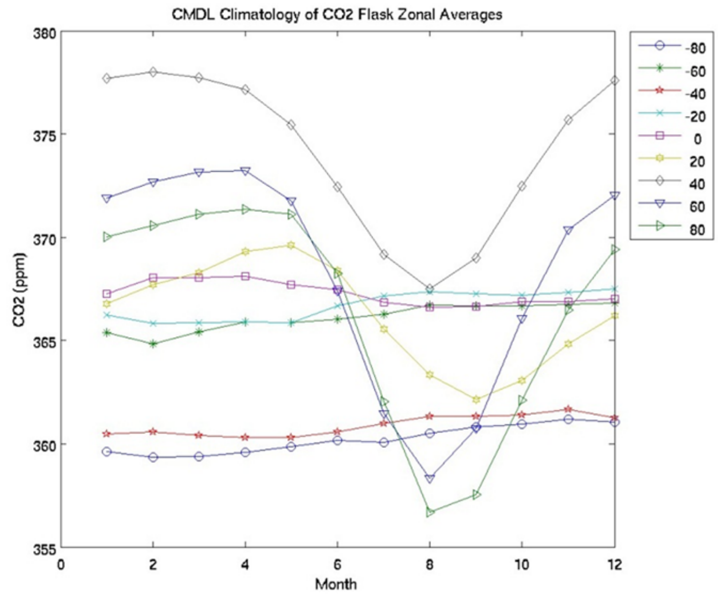

Figure 5. Zonal Average of NOAA CMDL measurements binned by month over the timeframe of the AIRS measurements.

4. PHASE LAG ANALYSIS

The seasonal variability in atmospheric CO_2 is driven by the annual uptake of CO_2 through the process of photosynthesis and the release of CO_2 through respiration. Notice that the process of detrending to create climatologies removes the annual increase due to human activity. Consequently, we would expect a phase lag between the peak in atmospheric CO_2 at the surface and the peak of the vegetative cycle. However, the AIRS measures CO_2 in the middle troposphere where there could be delays in the seasonal cycle due to atmospheric transport. In order to assess the phase lag in the middle troposphere, we fit the AIRS zonally averaged climatologies with a 1st order sinusoidal function to determine amplitude and phase. The same process is performed for the CMDL data and the Scripps data. Results are shown in Figure 6. Confidence intervals on the figures are obtained from a bootstrap statistical analysis and represent the 90% uncertainty intervals for the phase estimates.

Figure 6. Observed phase of the seasonal cycle of atmospheric CO_2 for AIRS (blue circles), Scripps (red diamonds), and NOAA CMDL Flask data (purple stars).

5. SUMMARY AND CONCLUSIONS

AIRS mid-tropospheric CO_2 representations are compared to ground-based measurements from Scripps and NOAA CMDL to observe differences in the seasonal cycle between the surface and the mid-tropospheric CO_2. Zonal averages are first computed to allow discrimination of the dependence of the seasonal cycle with latitude. The results show a significant phase delay between the surface and the middle troposphere, particularly in the northern hemisphere. The delay is lowest near the equator and increases towards the north pole. Since CO_2 is essentially an inert gas, it is an excellent tracer. The results indicate that the age of air in the middle troposphere is approximately 2 months older than that near the surface in the northern latitudes and significantly smaller in the tropics. The difference is likely due to the increased vertical mixing in the tropics due to higher convective activity. Results are less conclusive in the southern hemisphere and require further analysis.

ACKNOWLEDGMENTS

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